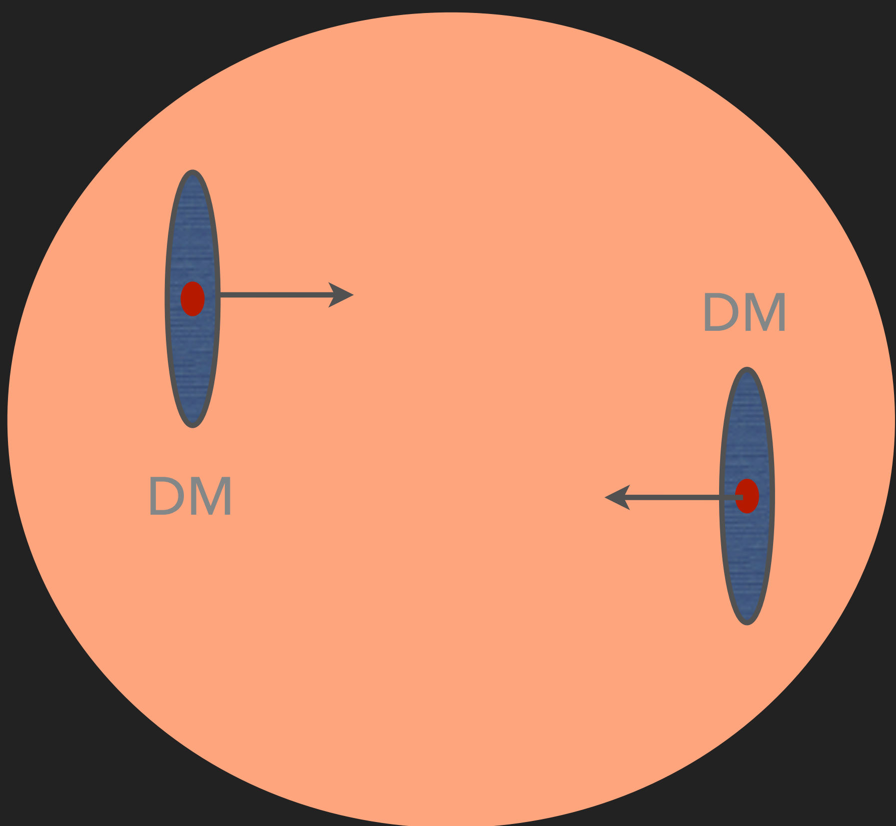
K. ZUREK

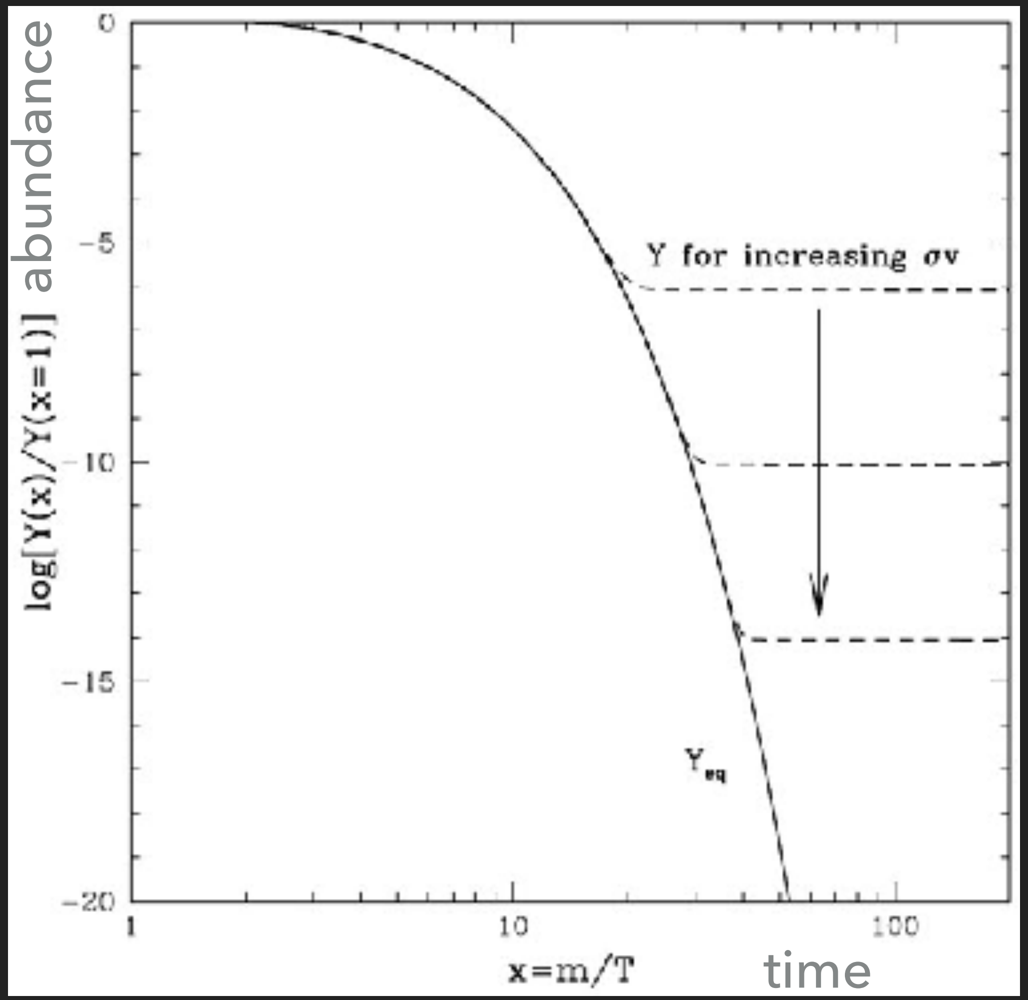
Leveraging the many faces (and phases) of matter

BROADENING THE SEARCHLIGHT: NEW IDEAS IN DARK MATTER DETECTION

NEW IDEAS IN DARK MATTER THEORY

- Old paradigm: weak scale dark matter (with relic density fixed by freeze-out)



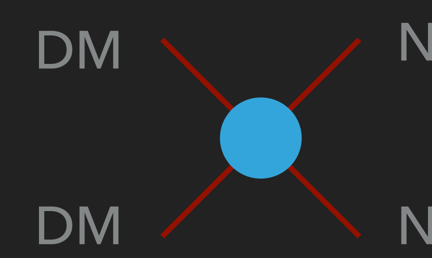


Kolb and Turner

$$n\langle\sigma v\rangle = H(T_{fo})$$

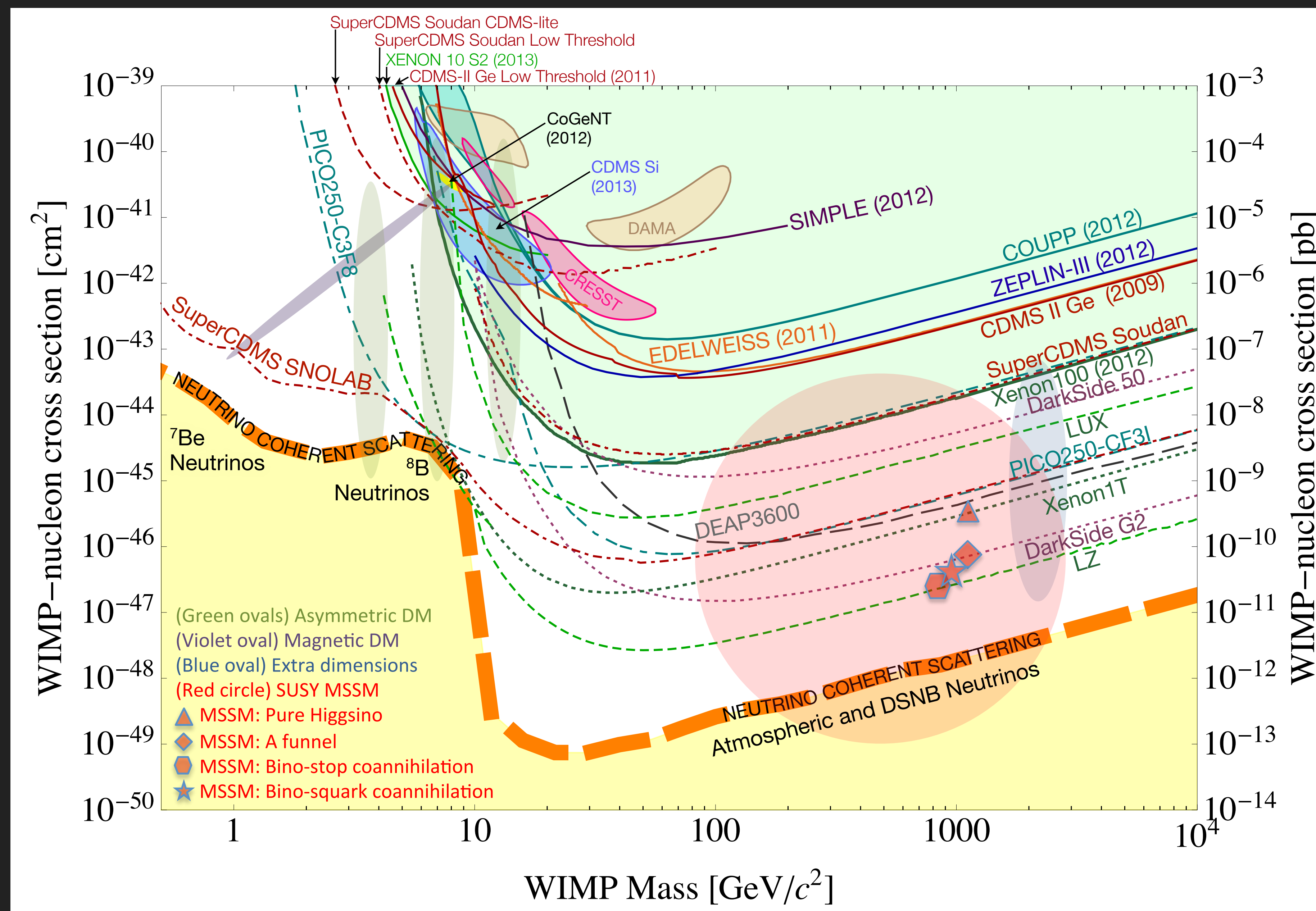
$$\implies \langle\sigma v\rangle \simeq \frac{1}{(20\ \mathrm{TeV})^2} \simeq \frac{g_{wk}^4}{4\pi(2\ \mathrm{TeV})^2}$$

WEAK SCALE PARADIGM: UNDER ASSAULT



Z-boson interacting dark matter: ruled out

Higgs interacting dark matter: active target



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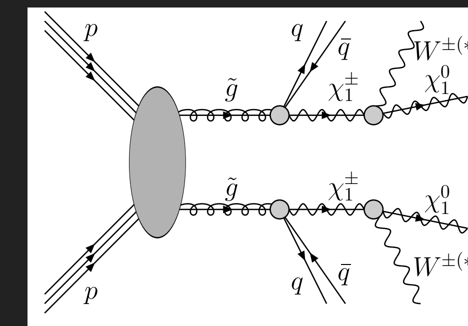
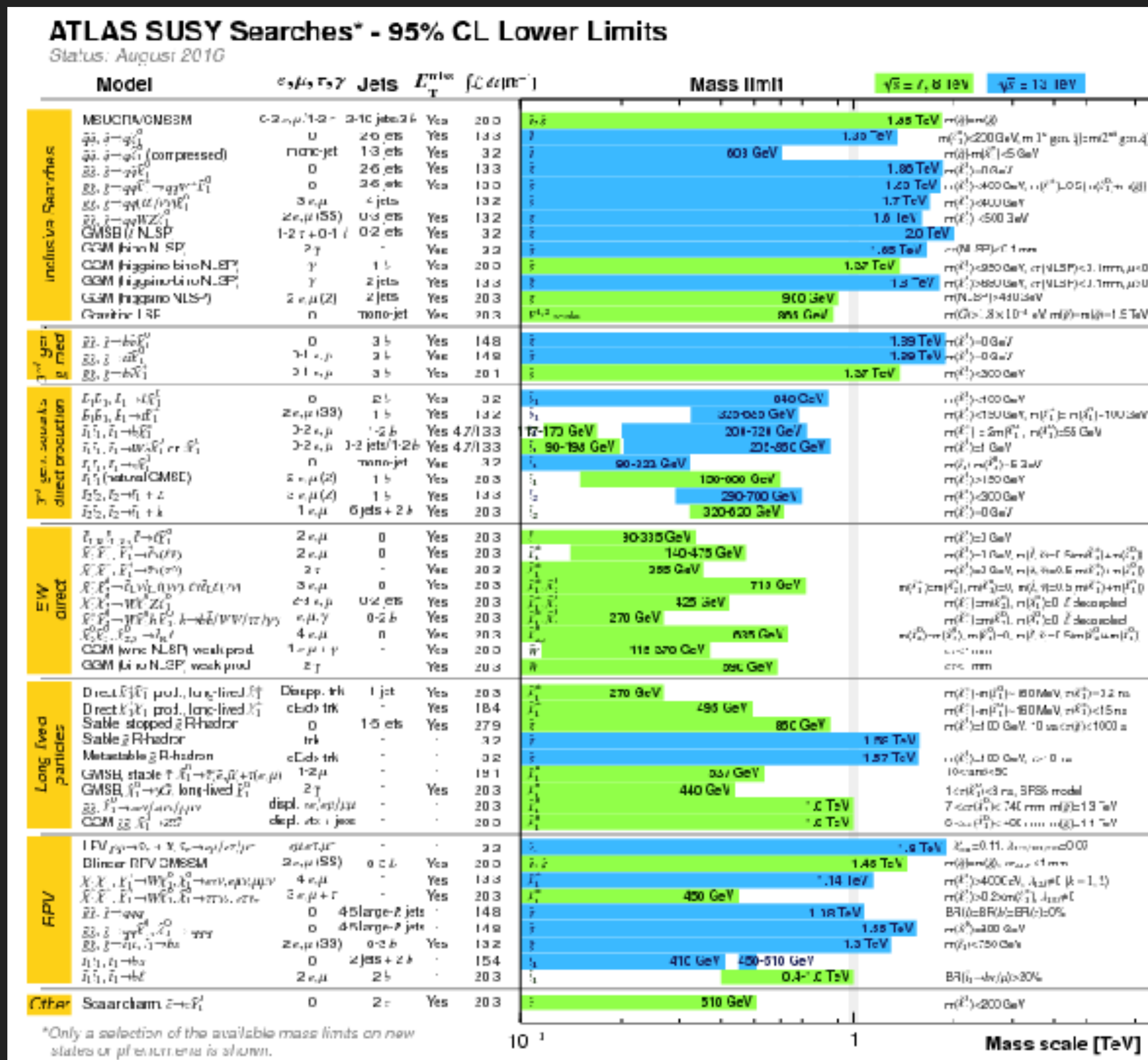




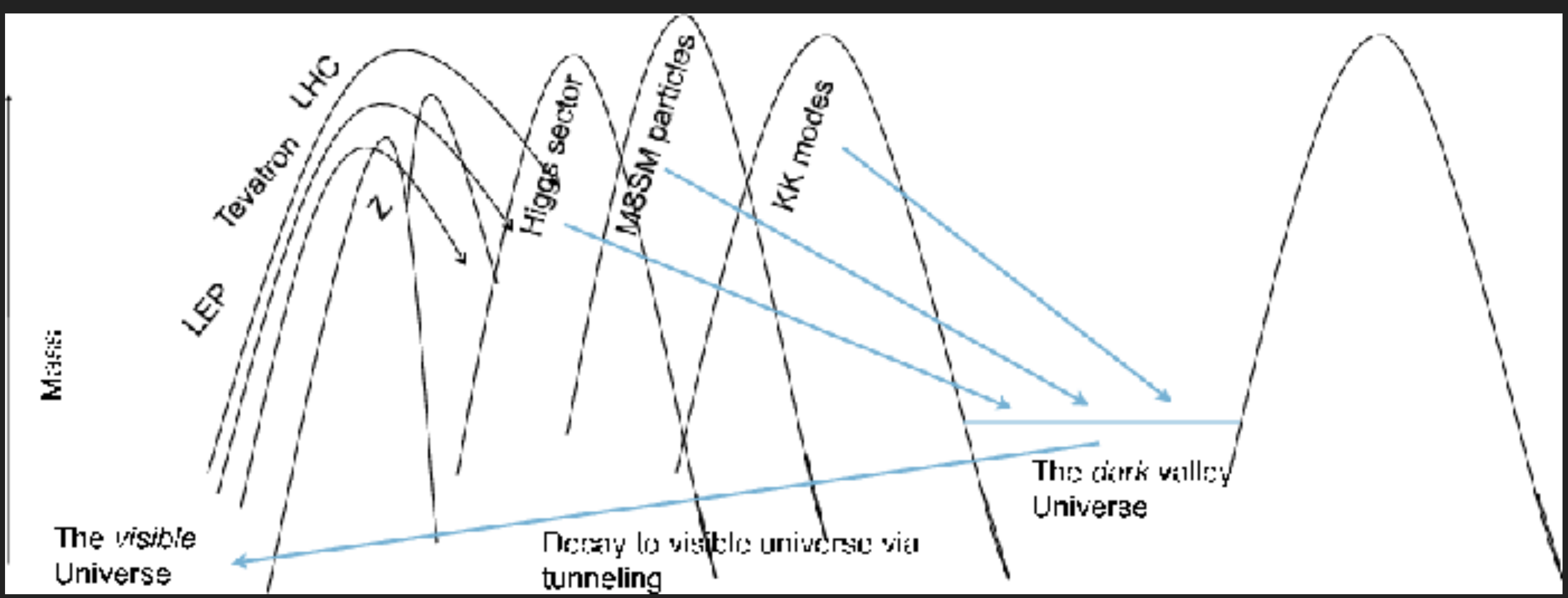
TOWARDS LIGHT DARK MATTER

Dark Matter May Reside in a Hidden Sector

Standard Model → Connector → Dark Matter

e.g. a stable dark pion

no weak force



$$\pi_v^+ \pi_v^- \to \pi_v^0 \pi_v^0$$

$$\pi_v^0 \to b\bar{b},\ \gamma\gamma$$

Hidden Valley paradigm, Strassler, KZ 2006

BROAD RANGE OF MODELS

Standard Model → Connector → Dark Matter

Supersymmetric

Hooper, KZ 2008, Feng and Kumar 2008

Arkani-Hamed, Weiner 2008

Baumgart, Cheung et al 2009 …

Baryogenesis

Buckley & Randall 2010, Cheung & KZ 2011

Fileviez-Perez & Wise 2010, 2013 …

Non-Abelian

Kribs, Roy, Terning, KZ 2009 …

Hidden Charged

Pospelov & Ritz 2007, Feng et al 2009 …

Dark Disk

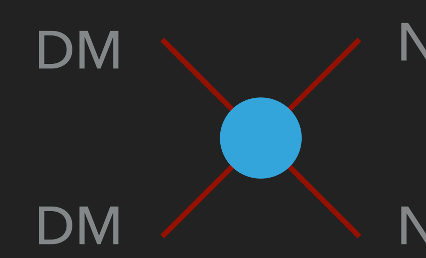
Fan, Katz, Randall, Reece 2013 …

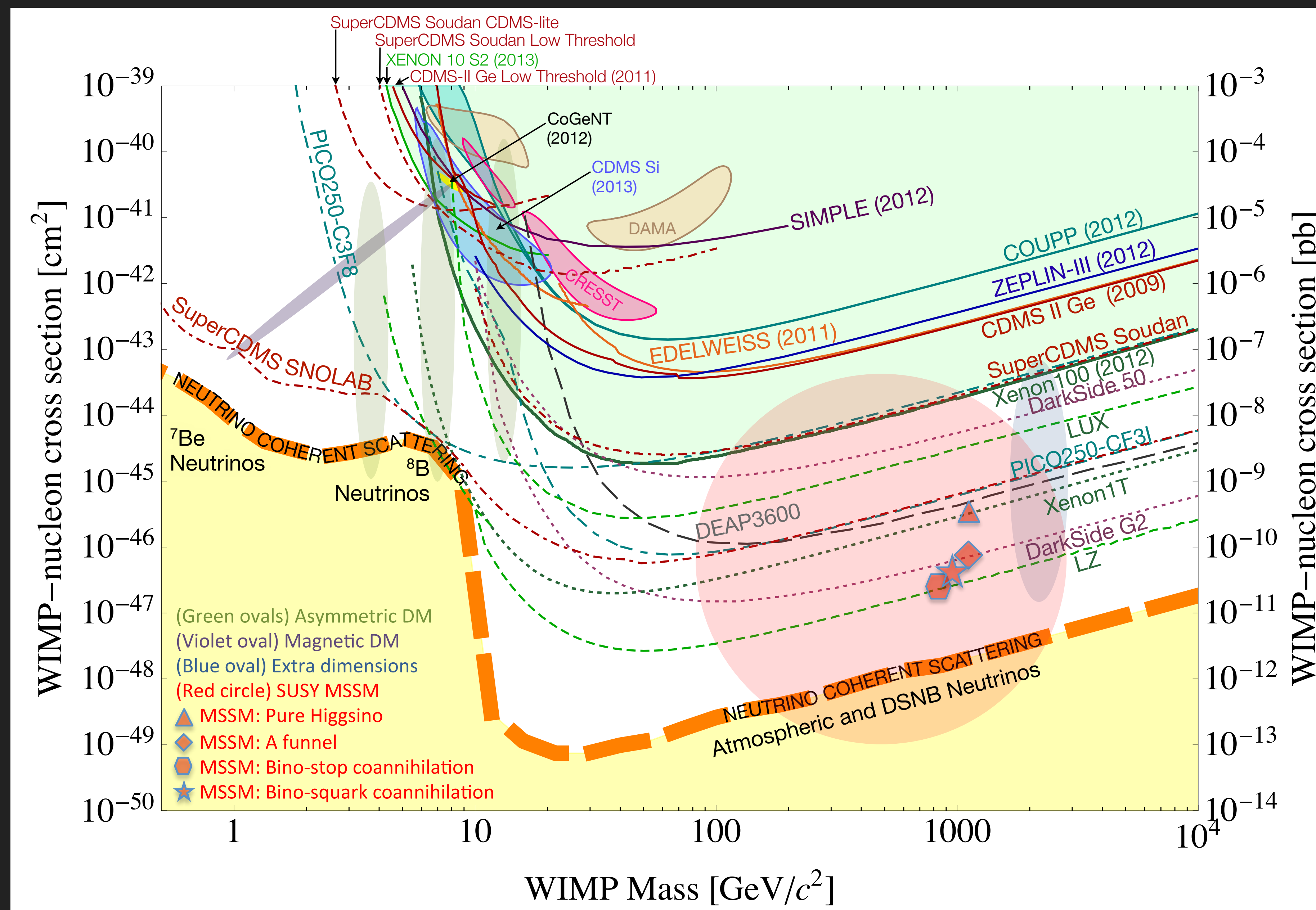
Atomic Kaplan et al 2009 …

Nuggets

Wise, Zhang 2014 …

WEAK SCALE PARADIGM: UNDER ASSAULT





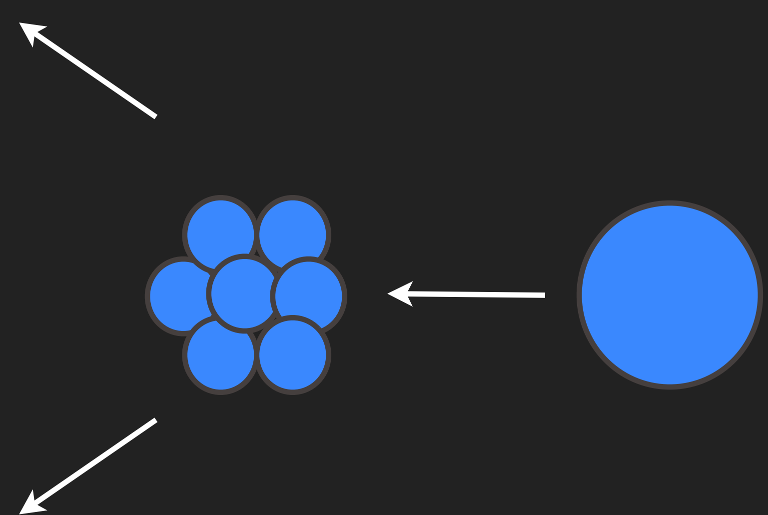
???

BROADENING THE SEARCHLIGHT

- New detection techniques to search for light dark matter
  - Sensitive to fainter whispers
    1. “Designer” materials
    2. Super-sensitive calorimeters with low dark counts
  - New modes to detect dark matter
    - Looking beyond billiard ball nuclear recoils

DIRECT DETECTION GOLD STANDARD

- Nuclear recoil experiments; basis of enormous progress in direct detection



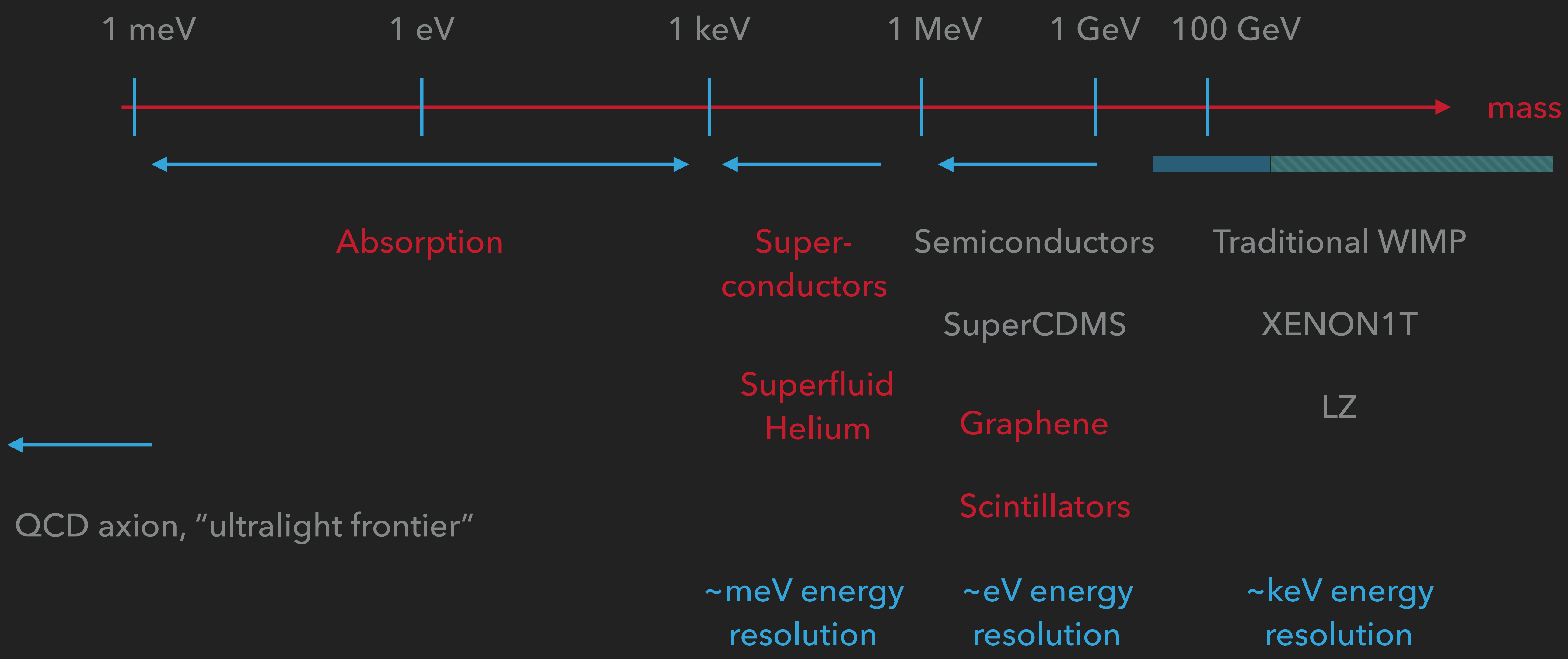
$v \sim 10^{-3} c$

$q, \;\; E_D$

$$\implies \; 2\mu_N v = q_{\max} = \sqrt{2 m_N E_D} \qquad \mu_N \equiv \frac{m_N m_X}{m_X + m_N}$$

$v \sim 300 \text{ km/s} \sim 10^{-3} c \implies E_D \sim 100 \text{ keV}$ for 50 GeV target

DARK MATTER LANDSCAPE



NUCLEAR RECOILS

- Kinematic penalty when DM mass drops below nucleus mass

$$E_D = \frac{q^2}{2m_N} \qquad q_{\max} = 2m_X v$$

$$E_D \gtrsim \text{ eV} \leftrightarrow m_X = 300 \text{ MeV}$$

even though $E_{\text{kin}} \gtrsim 300 \text{ eV}$

COLLECTING HEAT

- Basic hurdle for detecting light DM:

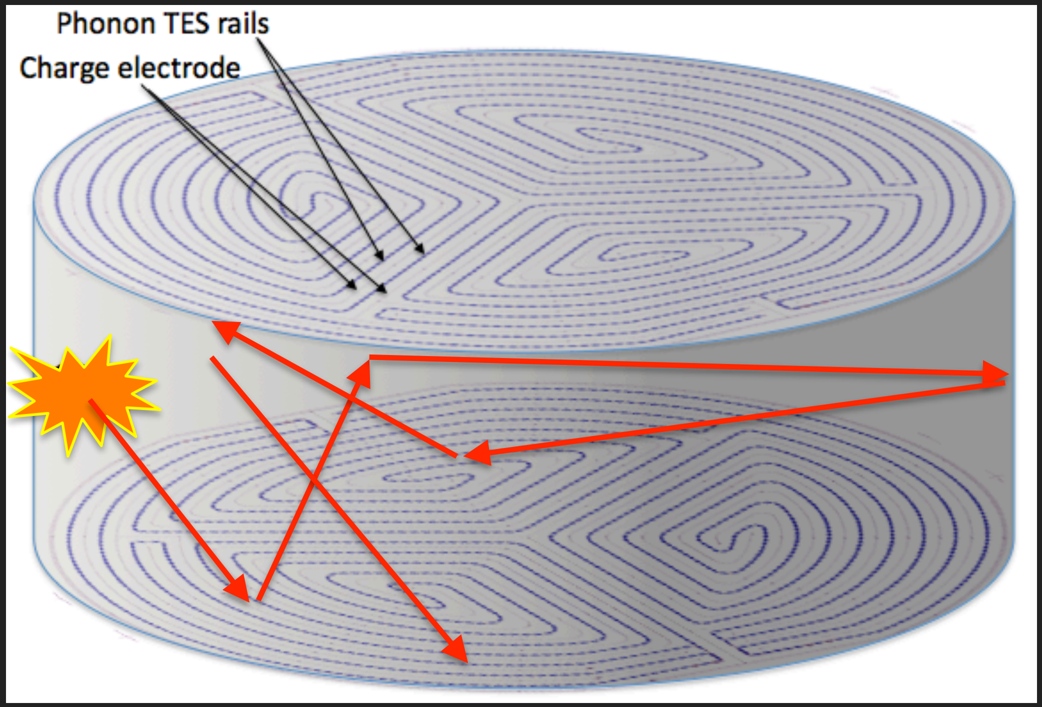
  Rare events with little energy deposit!

- Challenge: creating low enough noise environments to detect whispers
- Fundamentally limited by the gap
  - In atoms, ionization energy is at least 10 eV
  - In semiconductors, band gap is typically > 1 eV

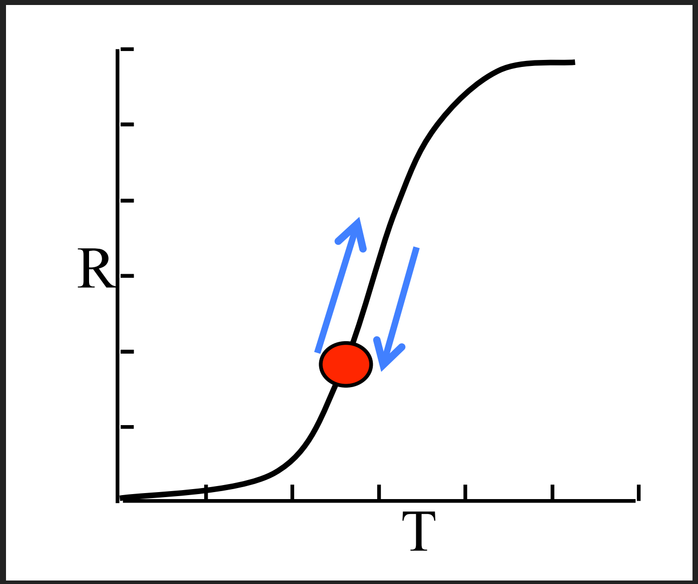
See talk by Pyle

COLLECTING HEAT

- Principles already in play in current direct detection experiments such as SuperCDMS
- Large target; concentrate small energy deposits onto small calorimeters



Transition Edge Sensor calorimeter



NEXT UP: ELECTRON

- More bang for the buck if DM lighter than 1 GeV

$$E_D = \frac{q^2}{2m_e} \qquad q_{\max} = 2 m_X v$$

- Allows to extract all of DM kinetic energy for DM MeV and heavier

$$E_D \gtrsim \ \mathrm{eV} \leftrightarrow m_X = 1 \ \mathrm{MeV}$$

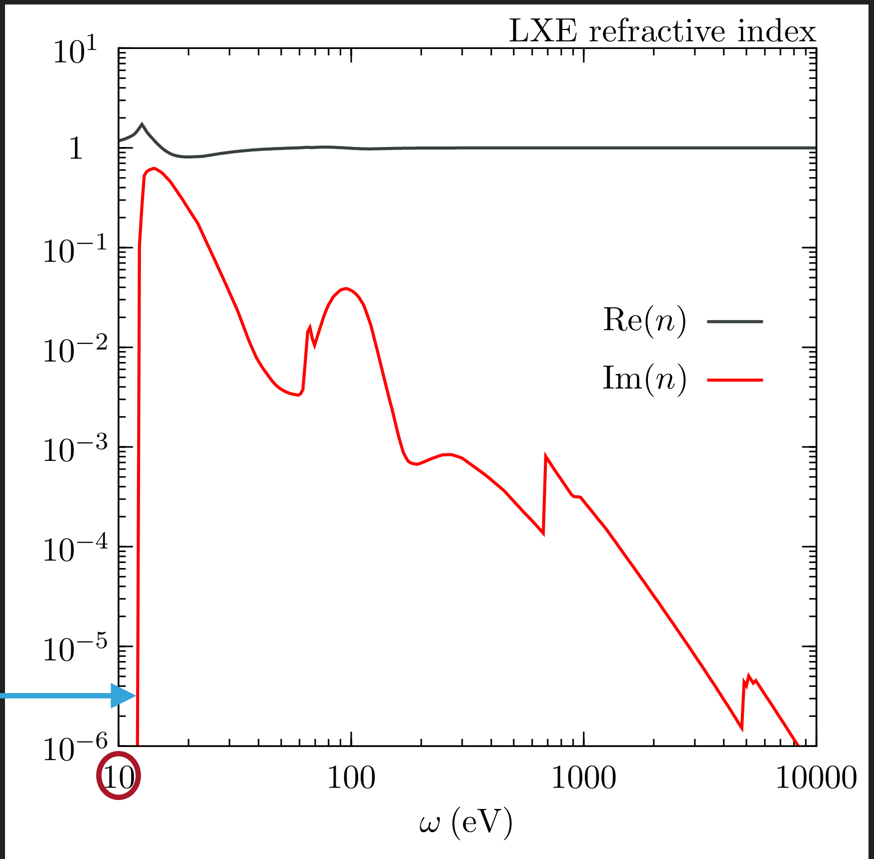
ELECTRONS IN MATERIALS

- In insulators, like xenon

  Tightly bound; ionize for signal

An, Pospelov, Pradler, Ritz 1412.8378

Gap!

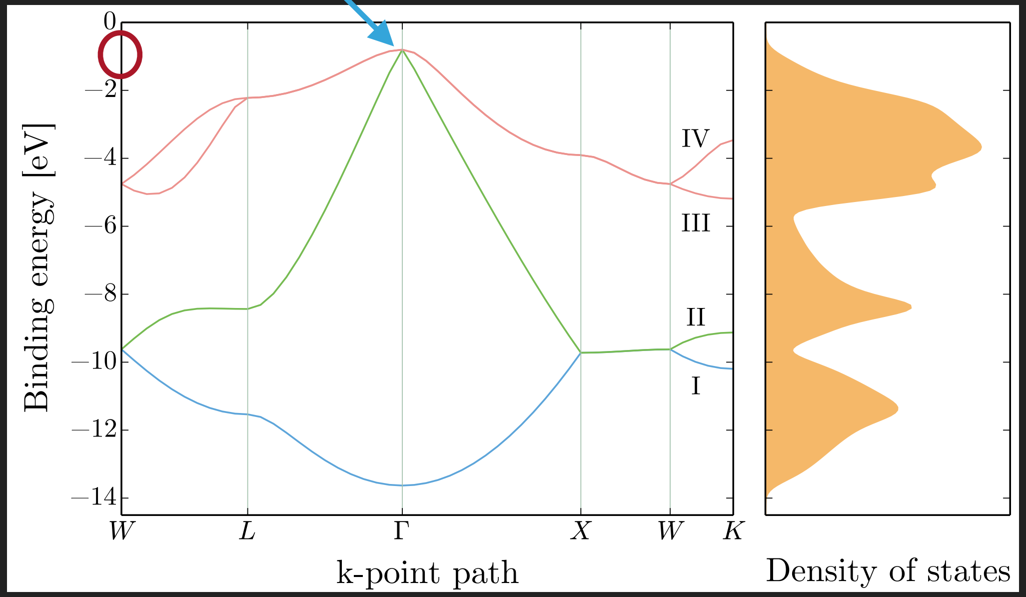


- In semi-conductors, like Ge, Si

  Valence electrons become conducting; presence of collective modes

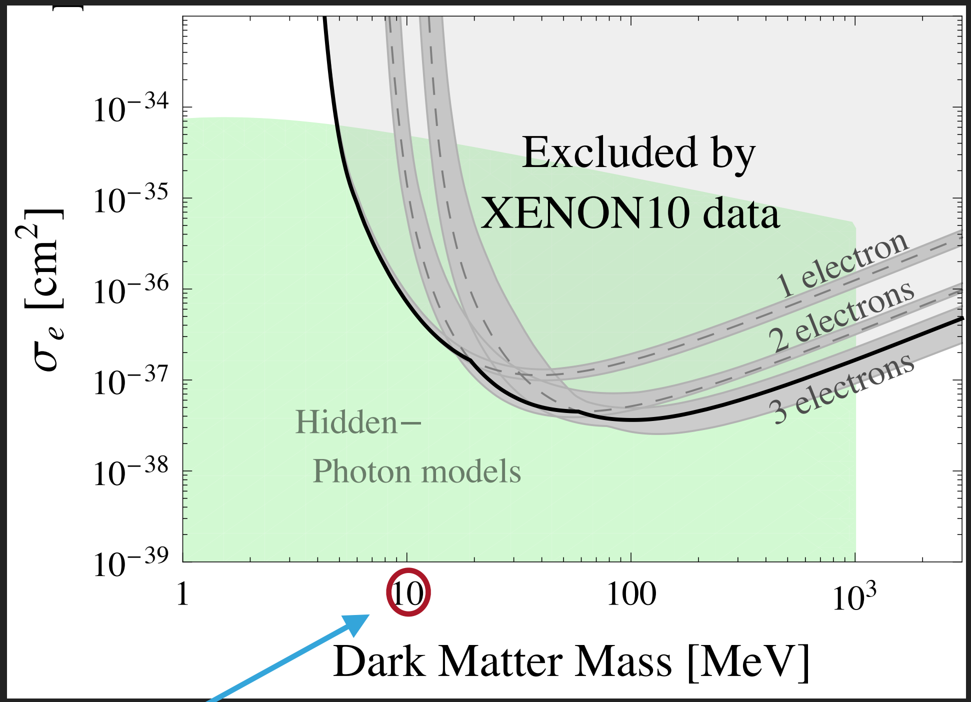
Gap!

Lee, Lisanti, Safdi 1508.07361



ELECTRONS IN MATERIALS

P. Sorensen et al 1206.2644

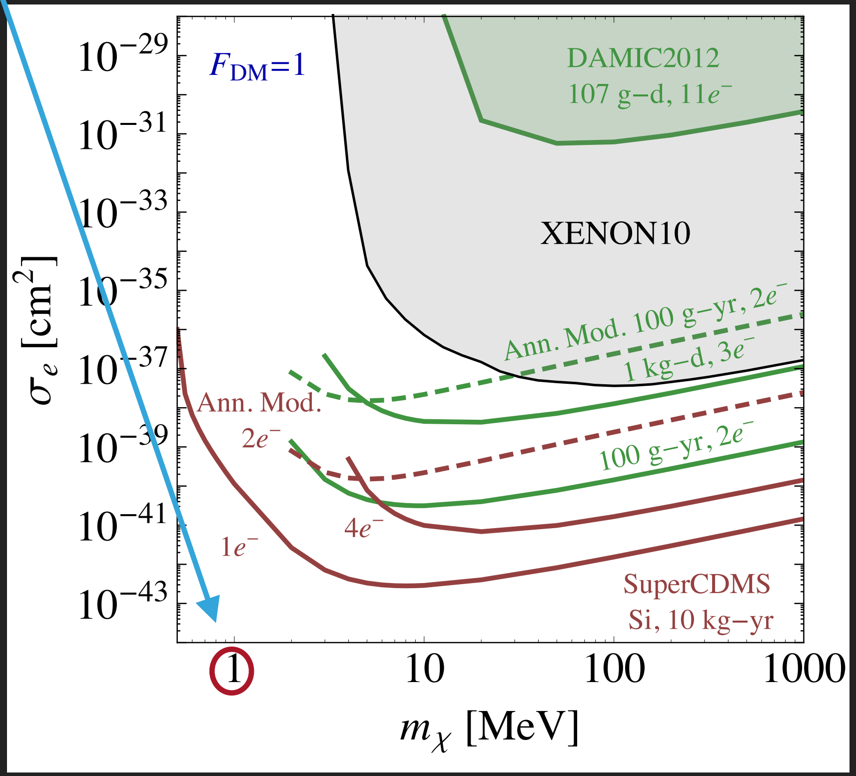


- In insulators, like xenon

  Tightly bound; ionize for signal

Gap = DM Kinetic Energy

Essig et al 1509.01598



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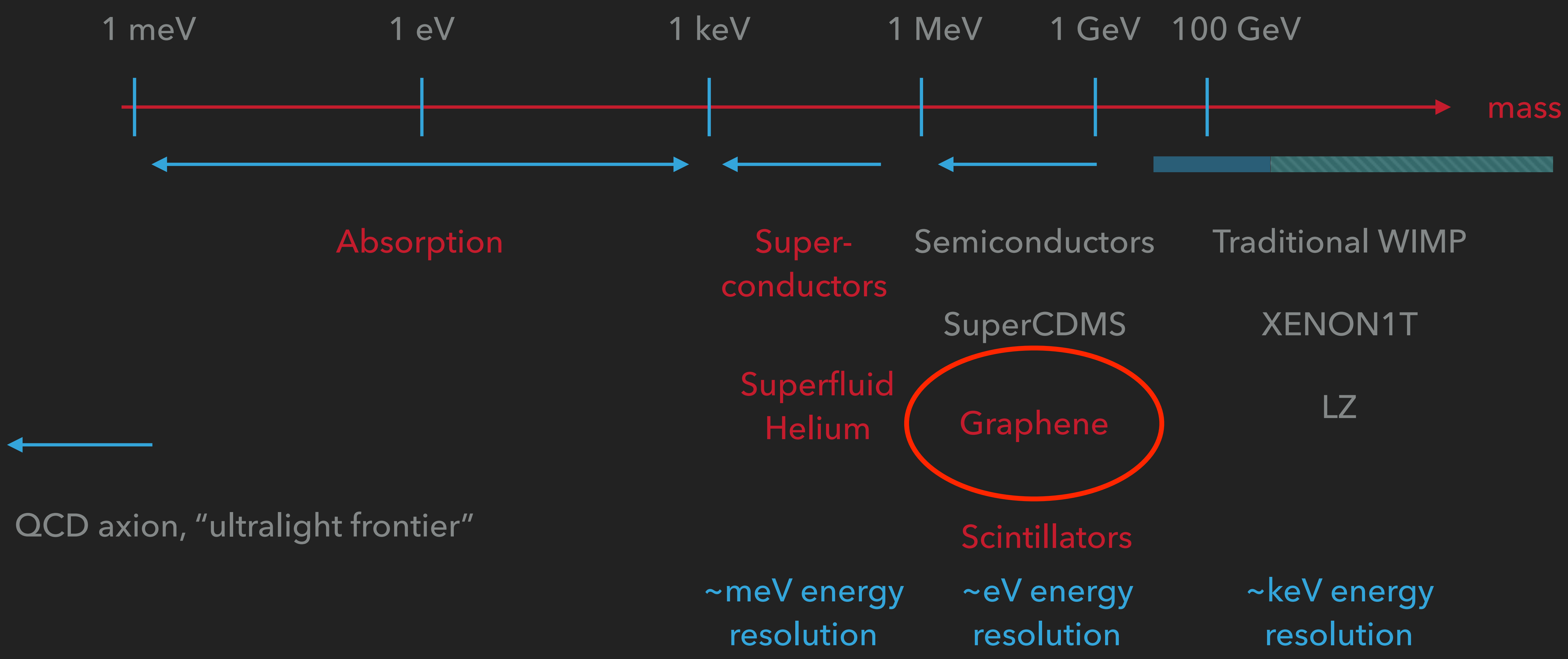
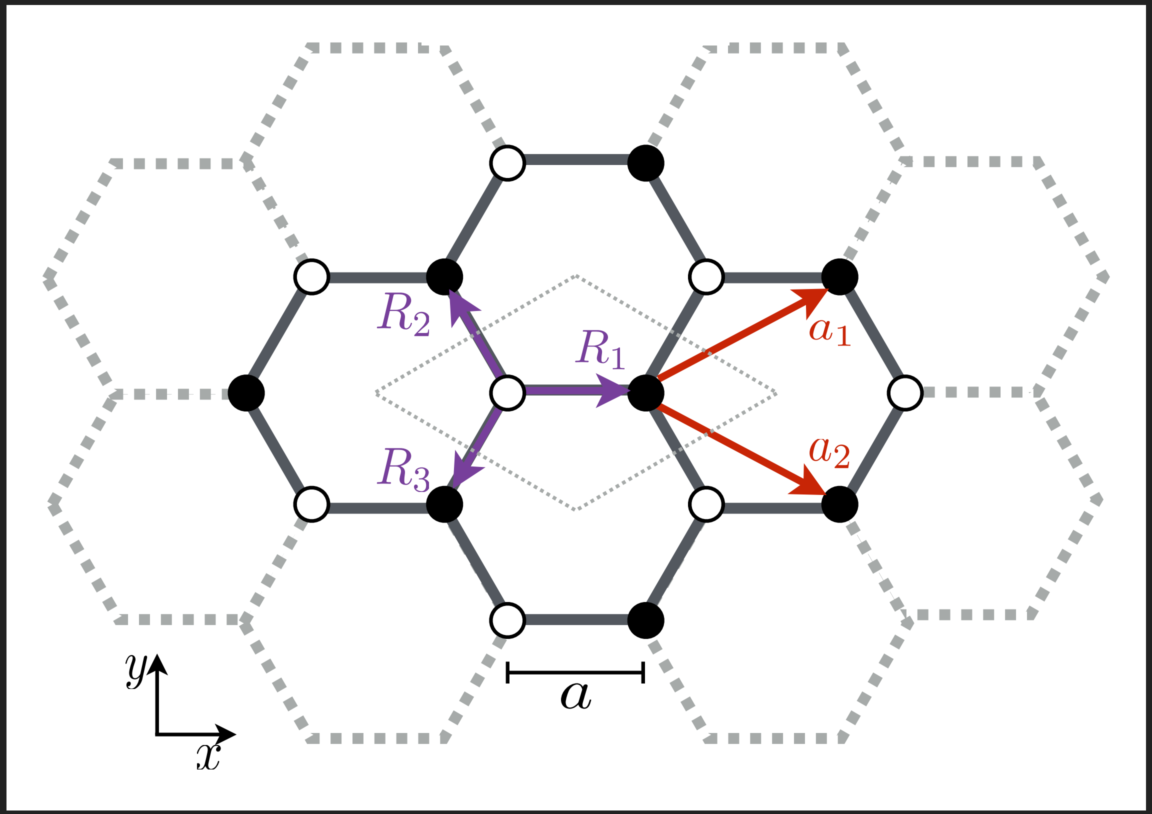
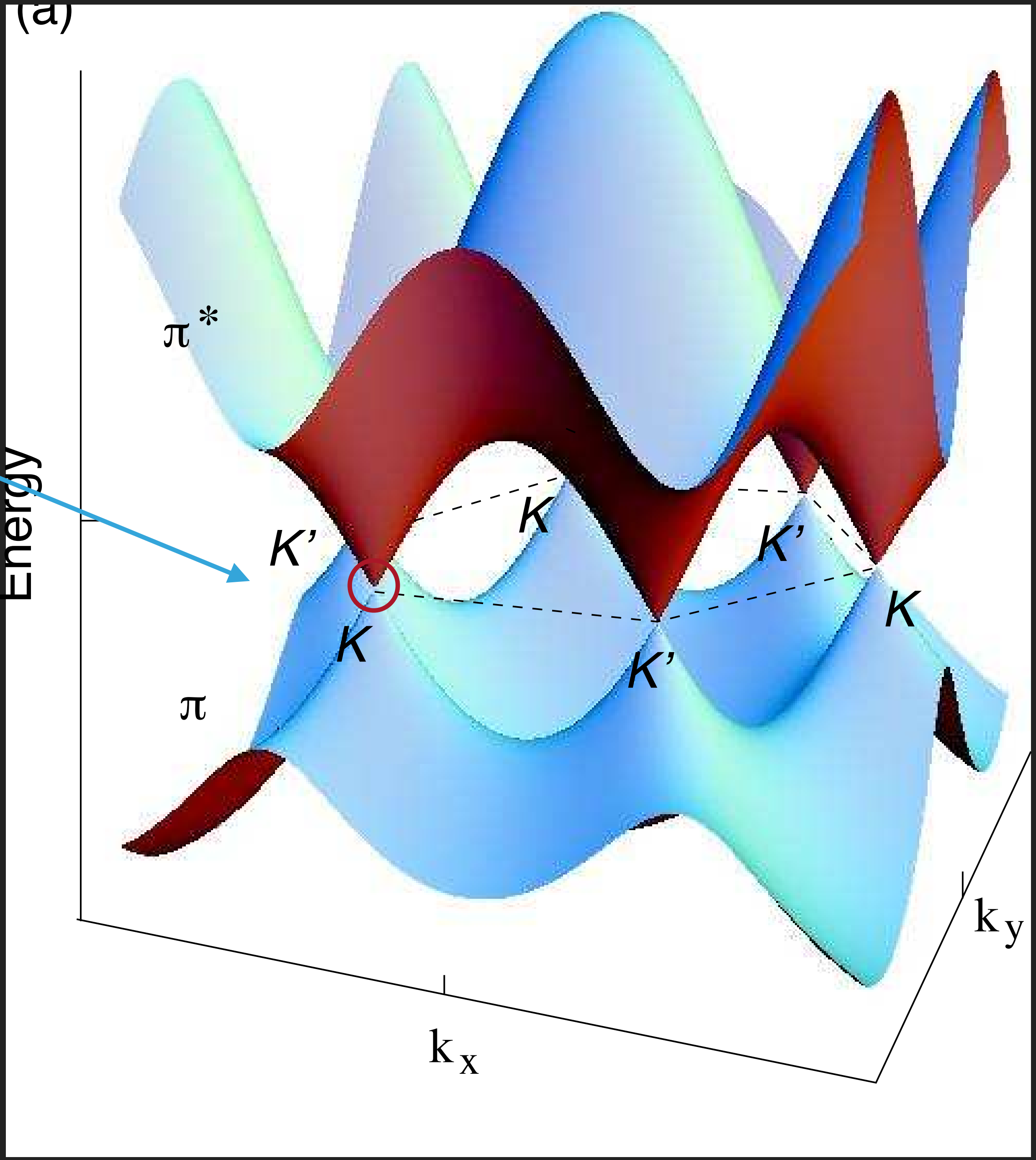
DARK MATTER LANDSCAPE



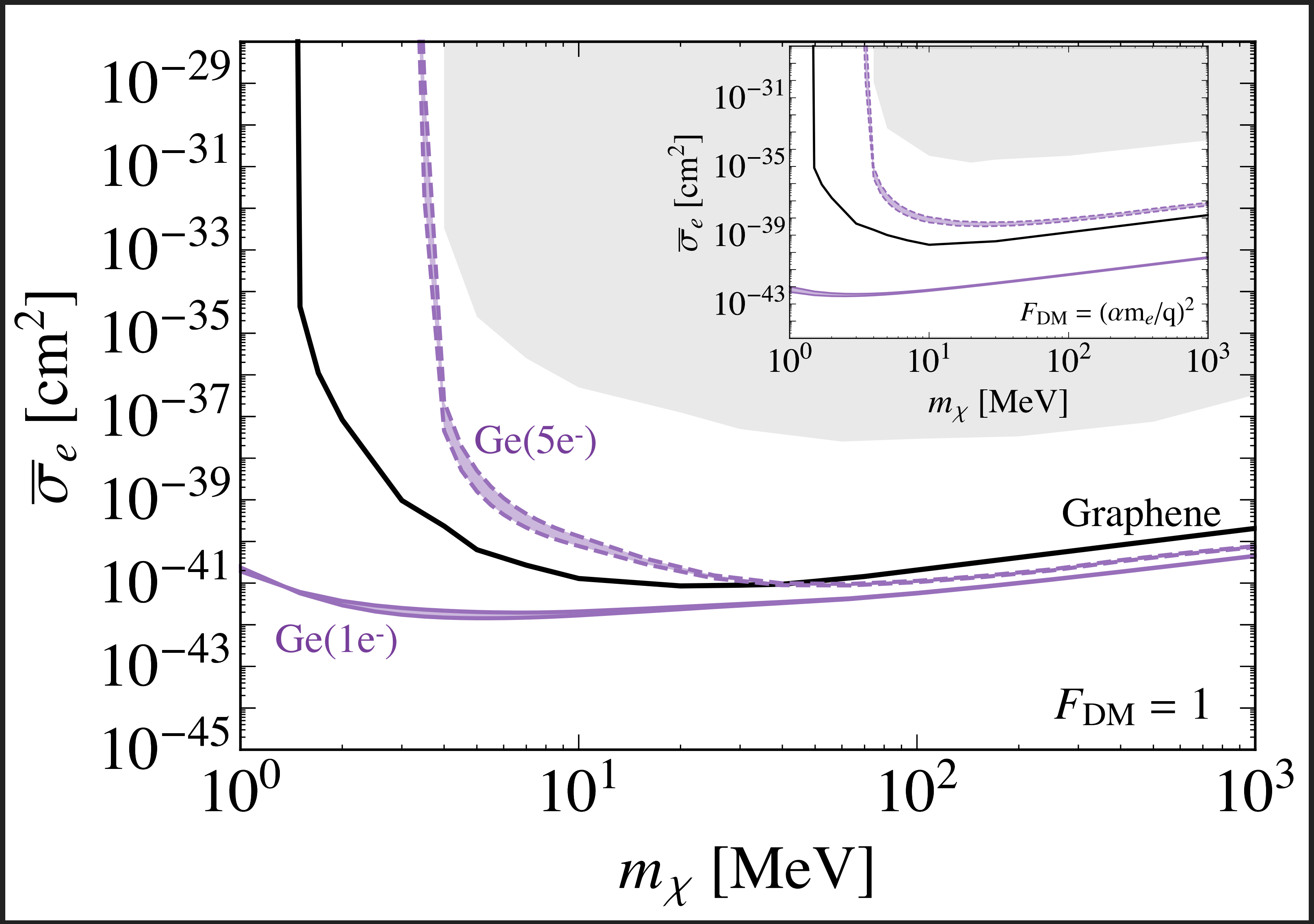
OTHER SMALL GAP MATERIALS — GRAPHENE

Symmetry structure of material gives rise to special points with no gap

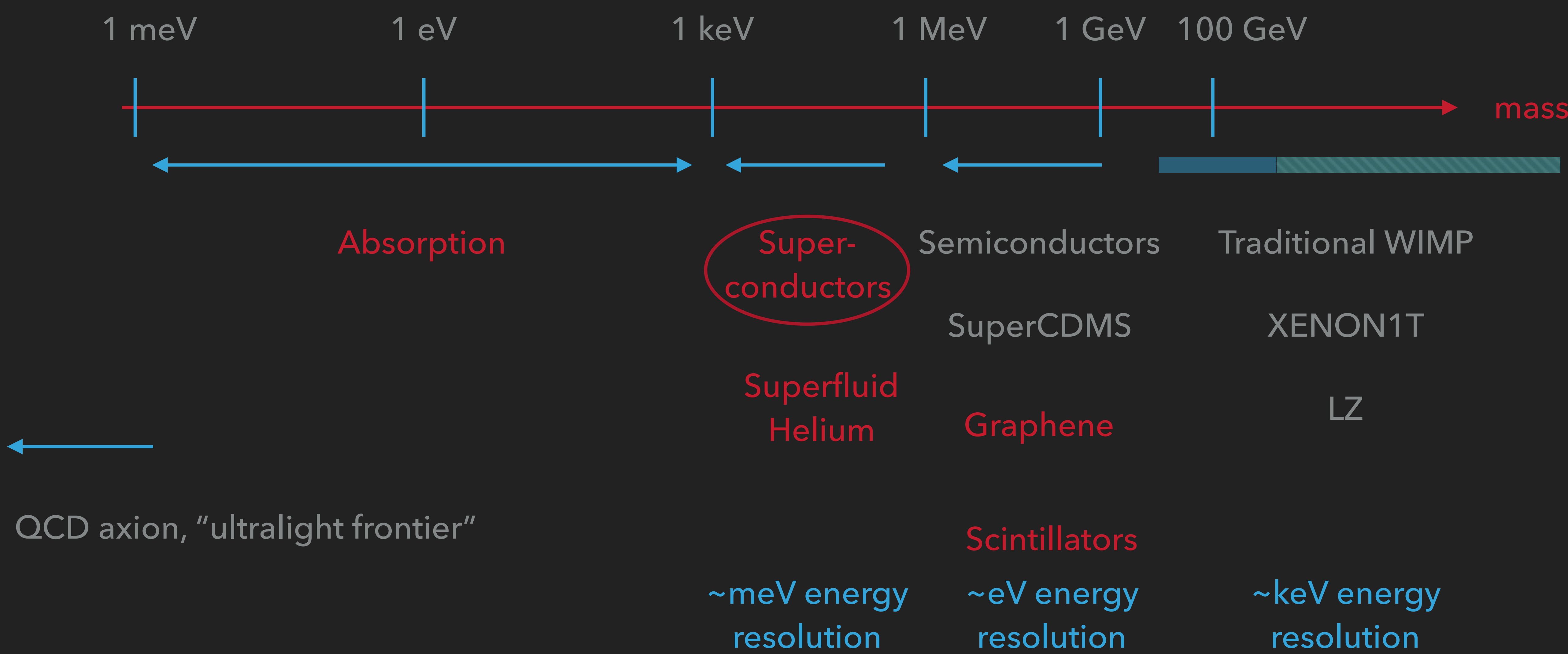




DARK MATTER RATE

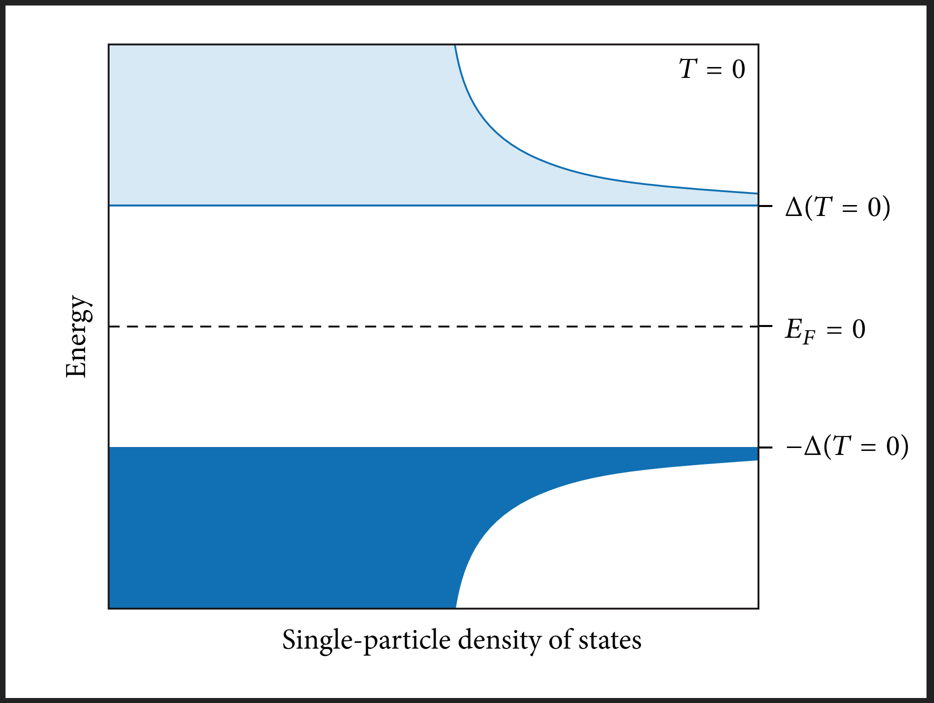


DARK MATTER LANDSCAPE

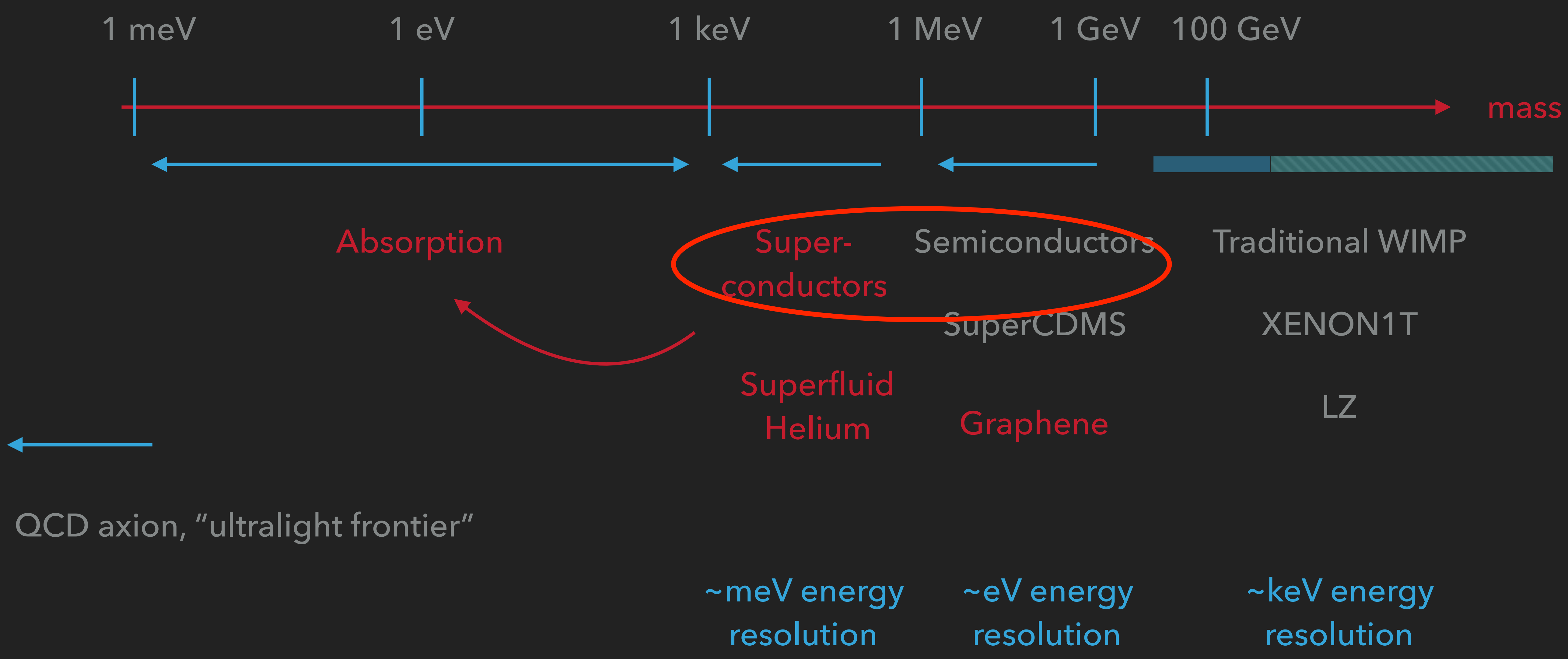


COOPER PAIRS

- Smaller gap $\Delta \simeq 0.3 \text{ meV}$
  - = more sensitivity to environmental noise
  - = more sensitivity to light dark matter

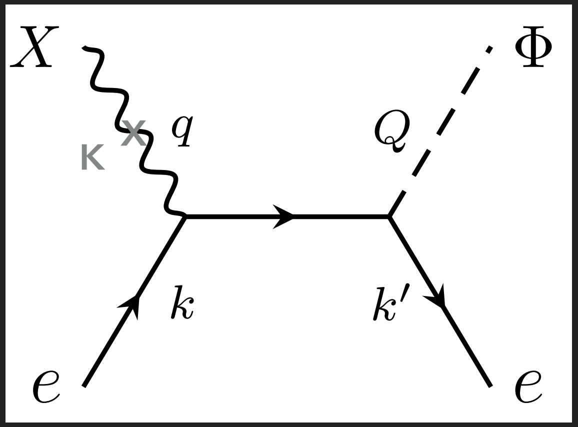


DARK MATTER LANDSCAPE

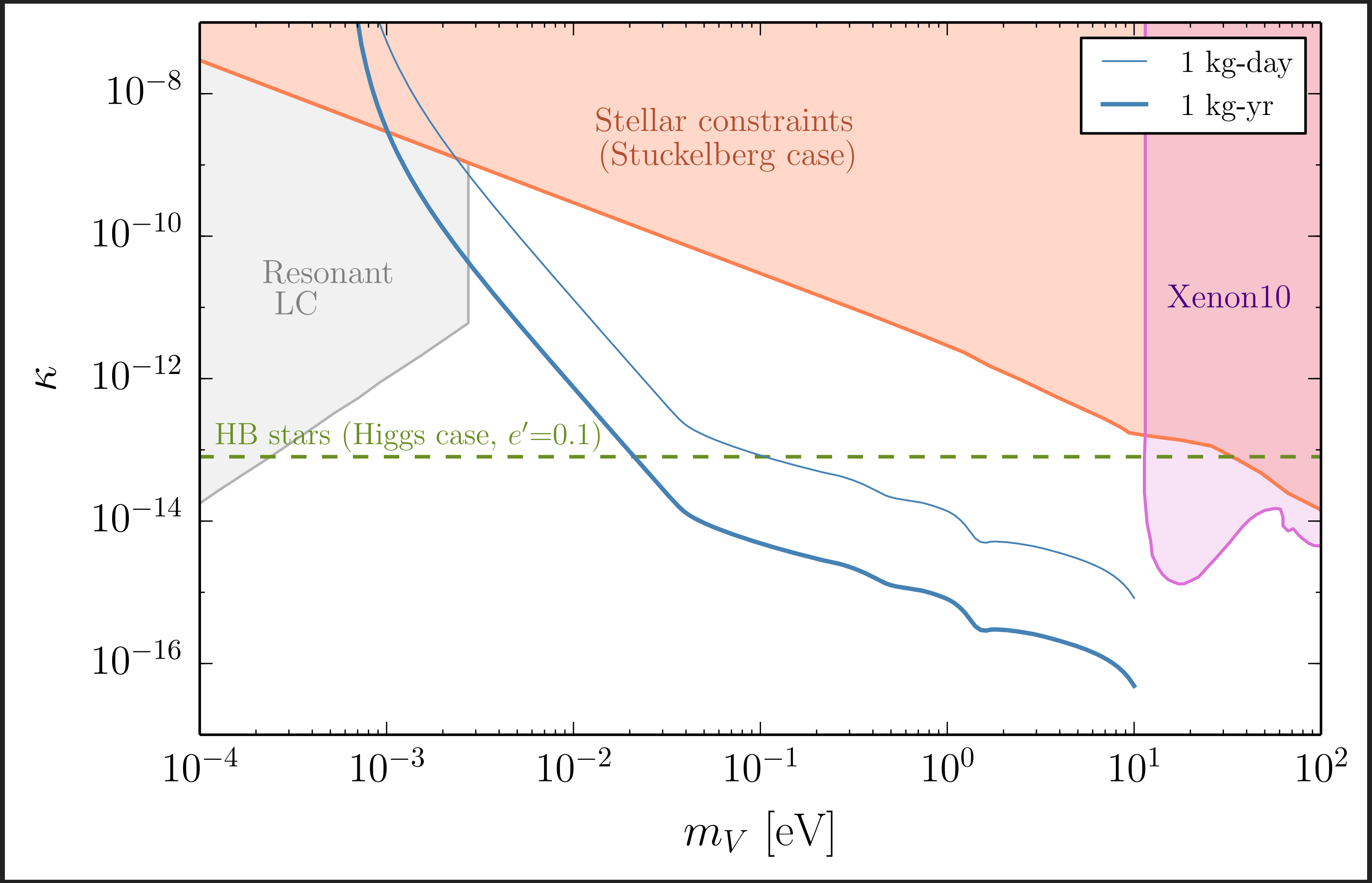


See T. Lin's talk

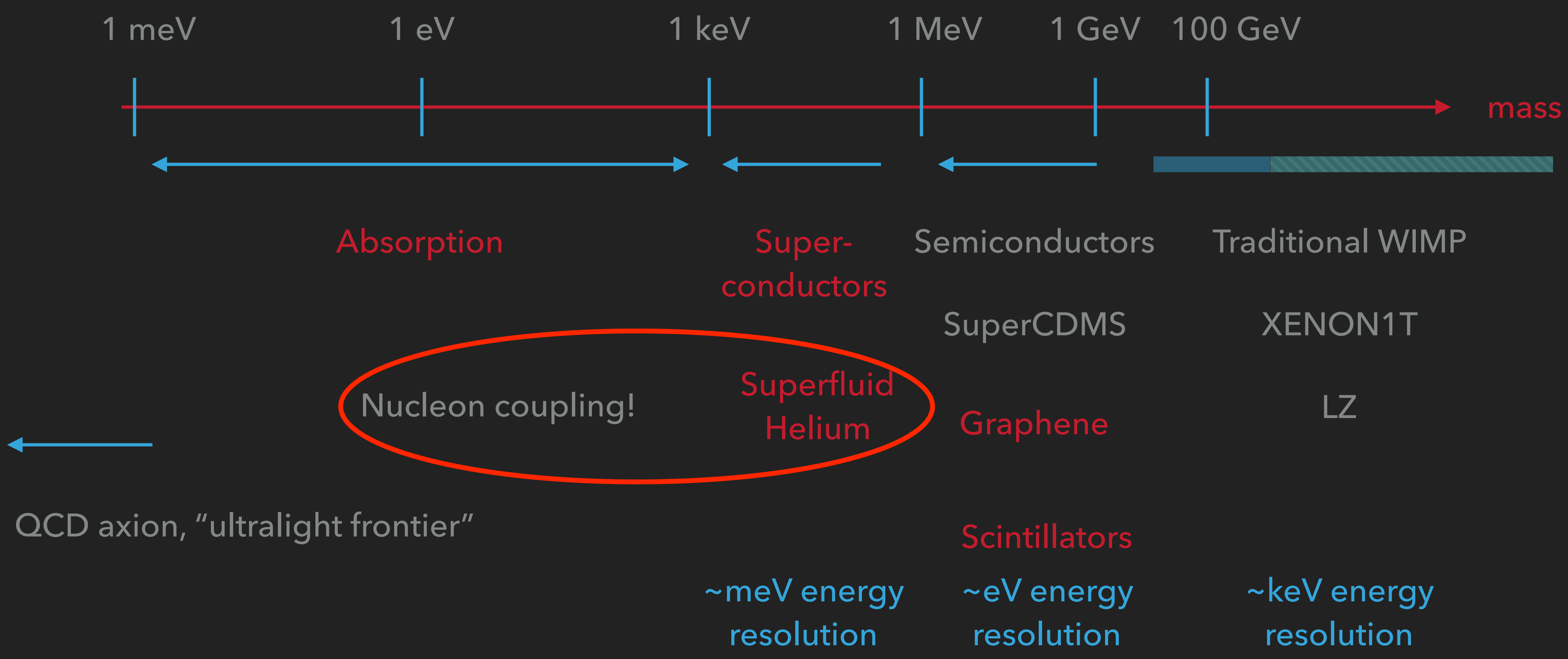
ABSORPTION



Dark Photon



DARK MATTER LANDSCAPE



Schutz, KZ 1604.08206; Knapen, Lin, KZ 1611.06228

LOW GAP MATERIAL

- Superfluids are naturally insensitive to noise. A good light DM detector? In the context of ordinary nuclear recoils, yes, see e.g. McKinsey's group 1605.00694

See talks this session

- To detect lighter DM, couple to phonon modes.

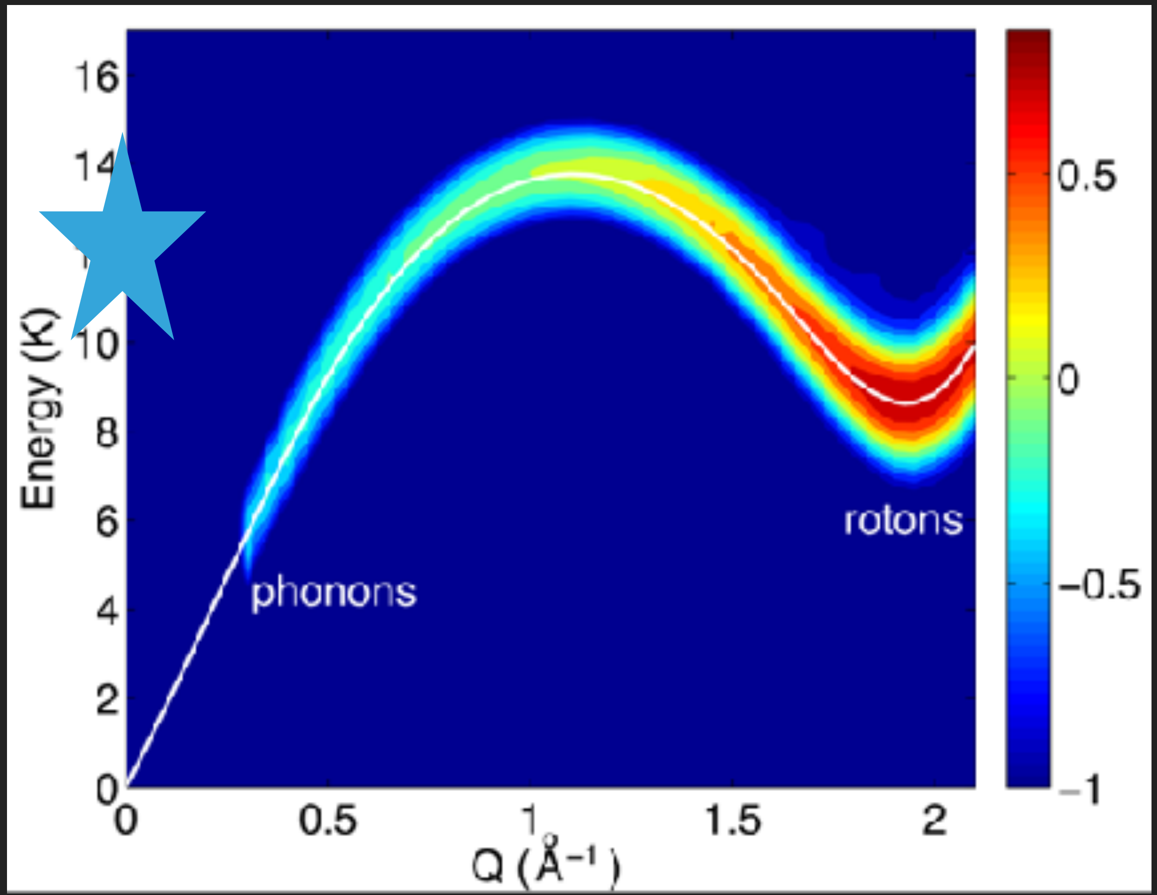
- Viable? At first glance – no

$$E_D \sim v_X q$$

vs

$$E_D \sim c_s q$$

$$c_s \ll v_X$$



- Next glance -- yes!

Schutz, KZ 1604.08206; Knapen, Lin, KZ 1611.06228

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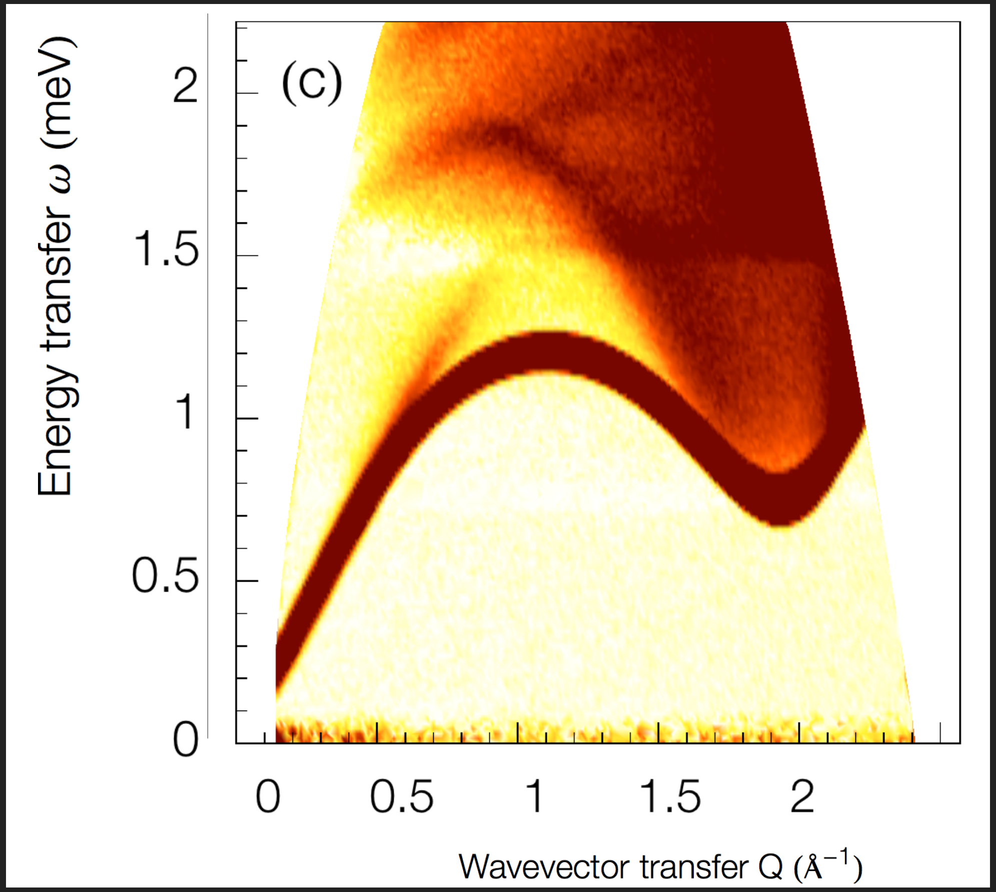
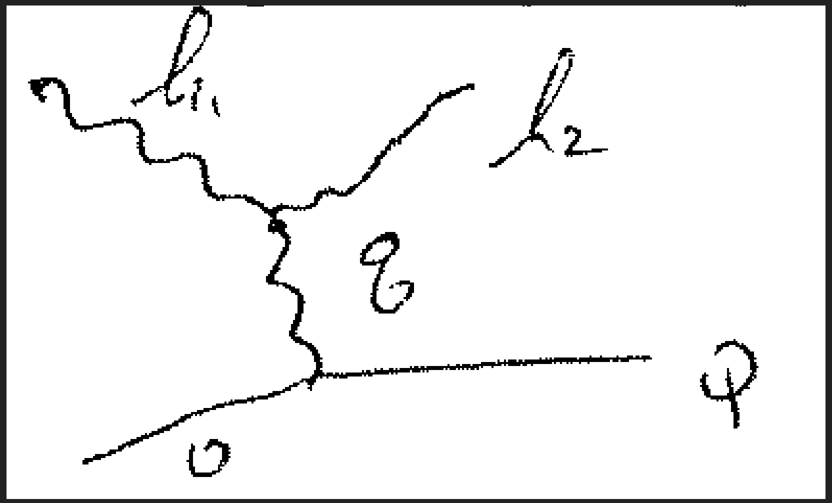


Beauvois et al 1605.02638

Schutz, KZ 1604.08206; Knapen, Lin, KZ 1611.06228

MULTI-EXCITATIONS

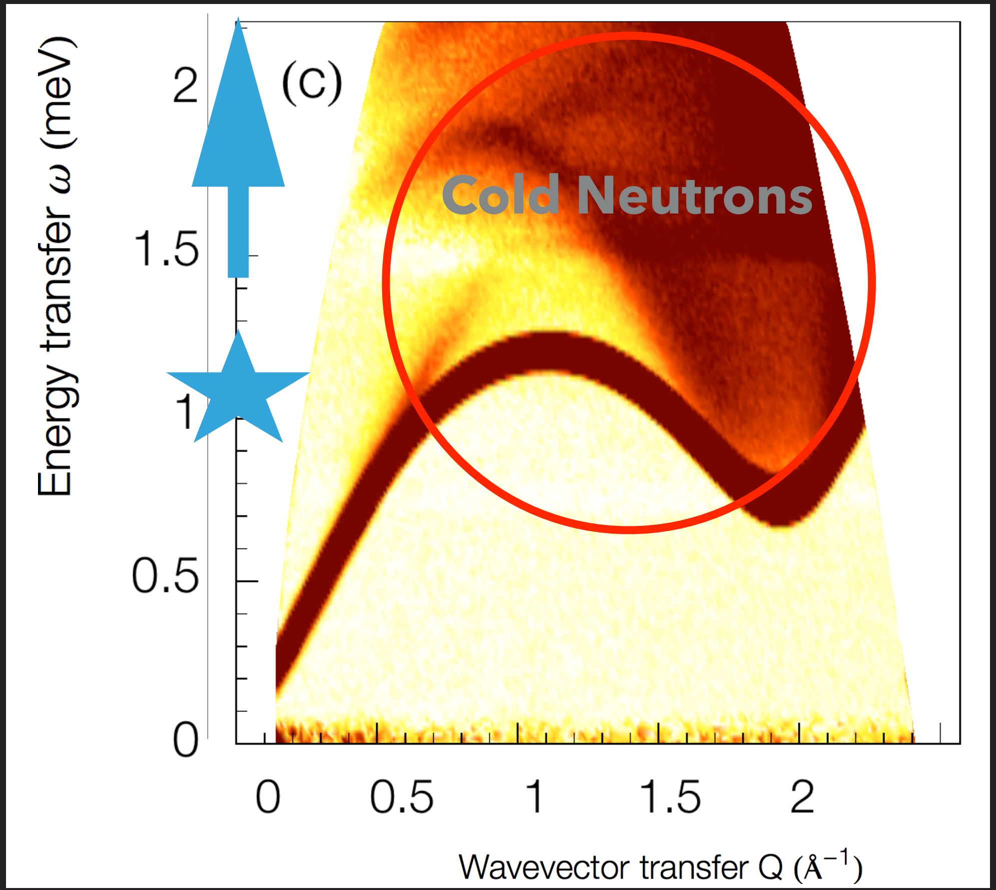
Internal note, R. Golub, 1977



- Calculated and observed for cold neutrons   See talk by E. Krotschek

$$V_3 = \int d^3r \left[\frac{\vec{v}\cdot\rho'\vec{v}}{2} \; \frac{1}{3!} \frac{d}{d\rho}\left(\frac{c^2}{\rho}\right)(\rho')^3 \right]$$

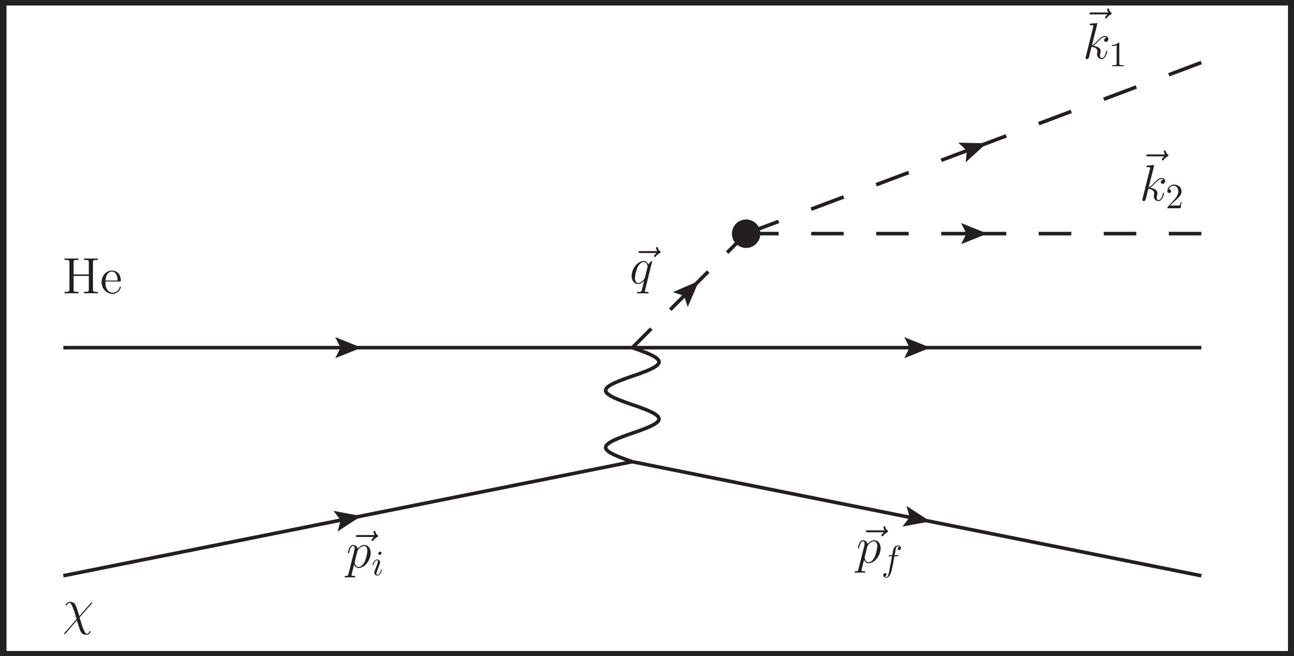
- However, this is in a very different kinematic regime
- No existing calculations in regime of interest



Beauvois et al 1605.02638

MULTI-EXCITATIONS

- emit back-to-back excitations to bleed off energy while conserving momentum



HOW TO CALCULATE?

- Theory developed by Landau-Khalatnikov and Feynman-Cohen
- Quantize the fluid Hamiltonian, like SHO

$$H_0 = \frac{1}{2}\sum_k \left(\rho_0 v_{\vec{k}} v_{-\vec{k}} + \phi(k)\rho_{\vec{k}}\rho_{-\vec{k}}\right) \qquad m_{\mathrm{He}}^2 S(k) = \langle \rho_k \rho_{-k} \rangle$$

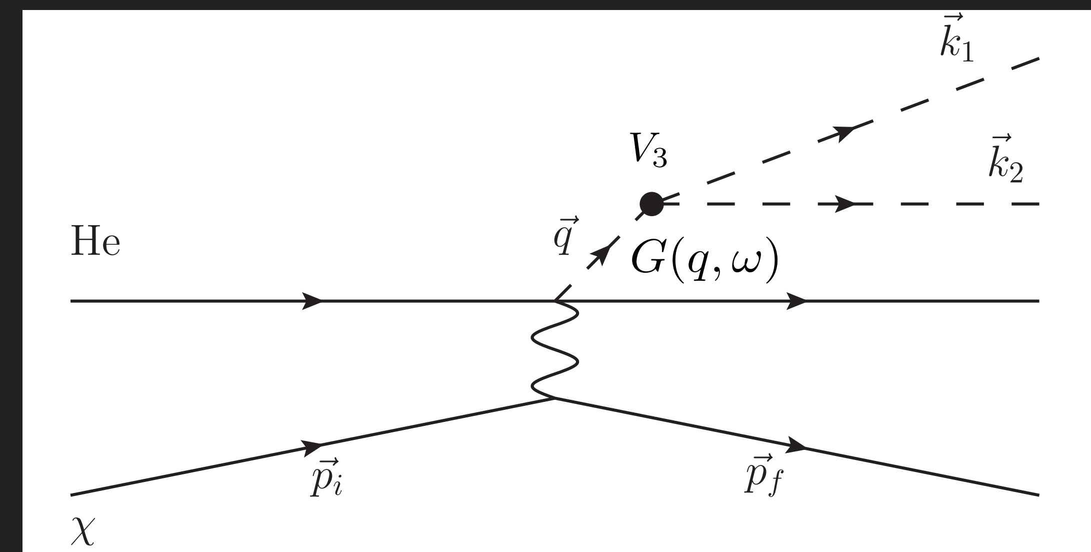
- Fluid is strongly coupled; excitations are propagating in interacting background (requires care)

RATE

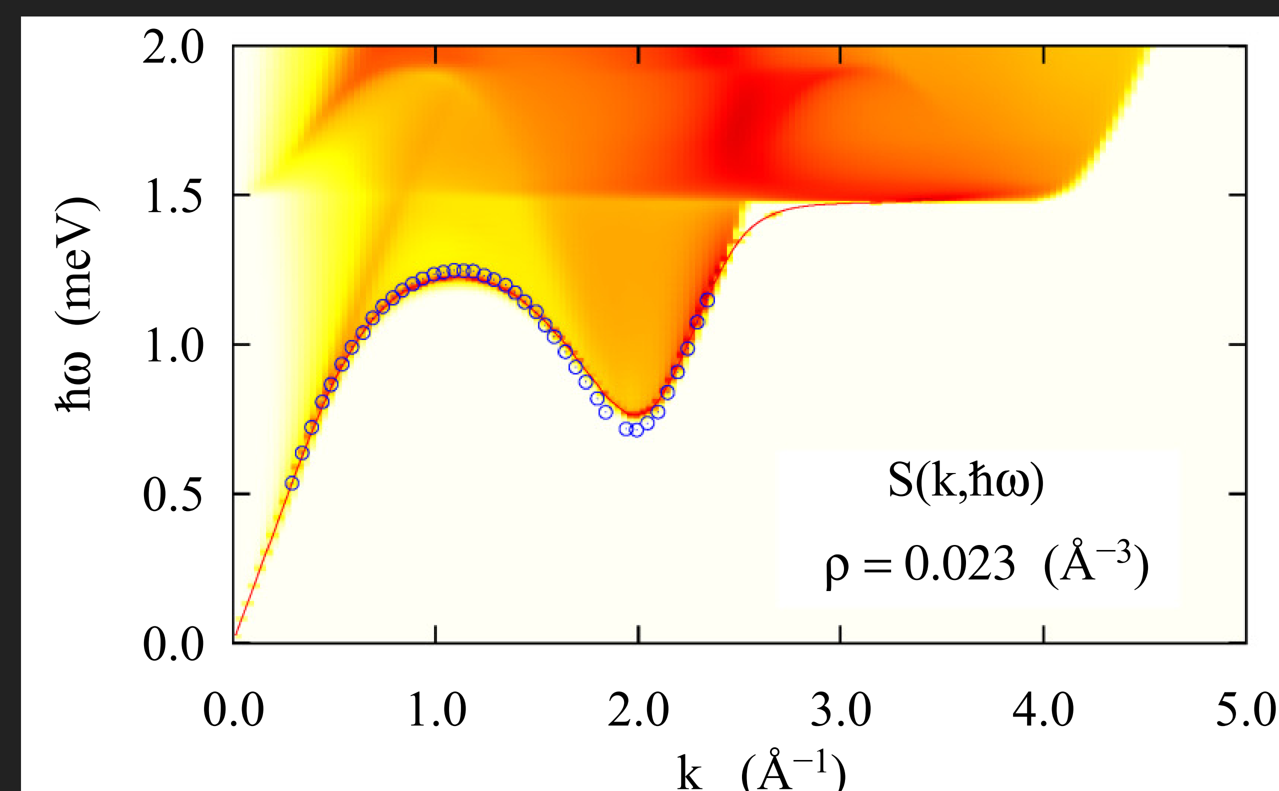
- Compute

$$(\vec{k}_1\vec{k}_2|H_3|\vec{q}) = -\frac{\left(\vec{q}\cdot\vec{k}_1U(k_1)+\vec{q}\cdot\vec{k}_2U(k_2)+q^2U(k_1)U(k_2)\right)}{2m_{\rm He}(S(q)S(k_1)S(k_2))^{1/2}}$$

$$G(q,\omega)\sim\frac{1}{\omega}$$

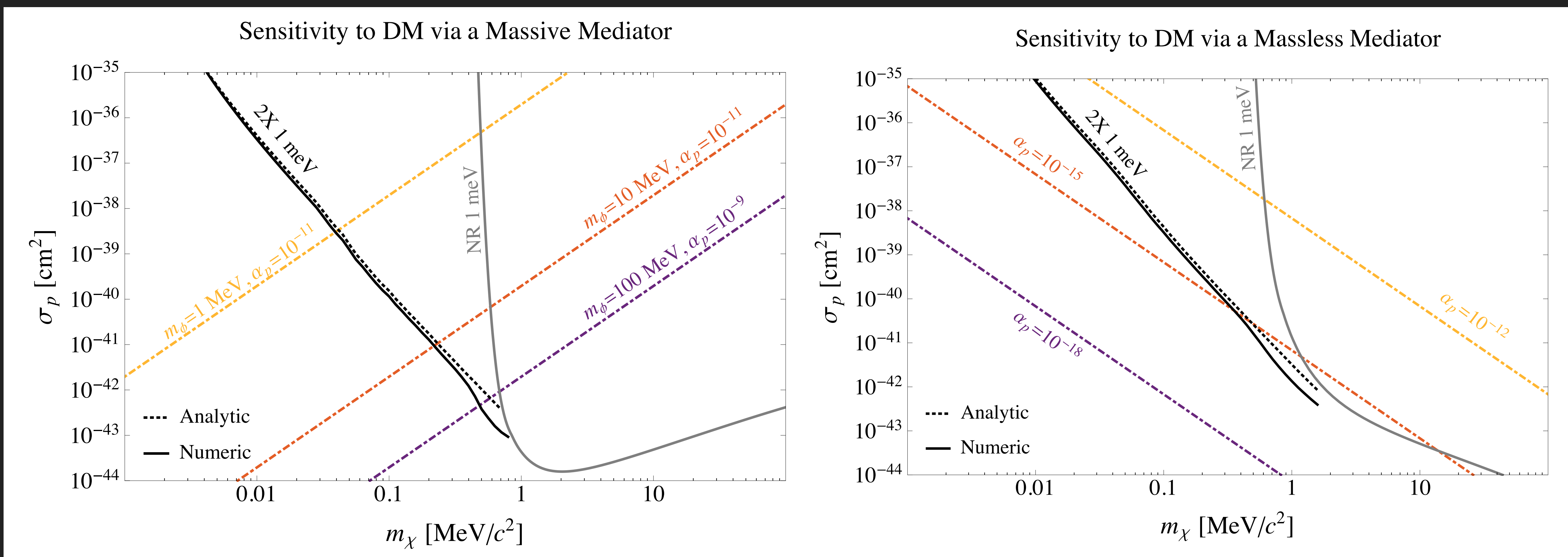


- Or, use simulation data



Campbell, Krotschek, Lichtenegger
Phys Rev B 91 184510

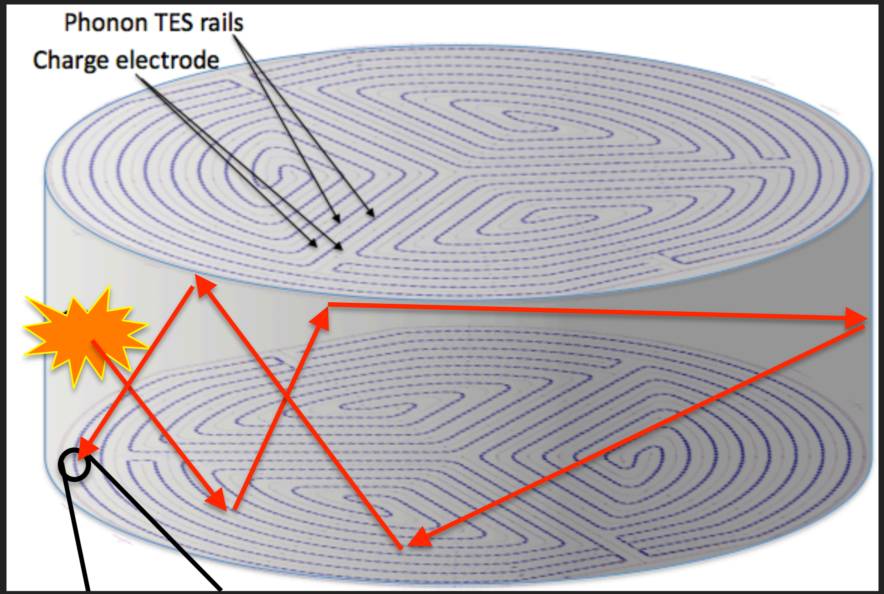
RESULTS



Great potential!

ROAD FORWARD

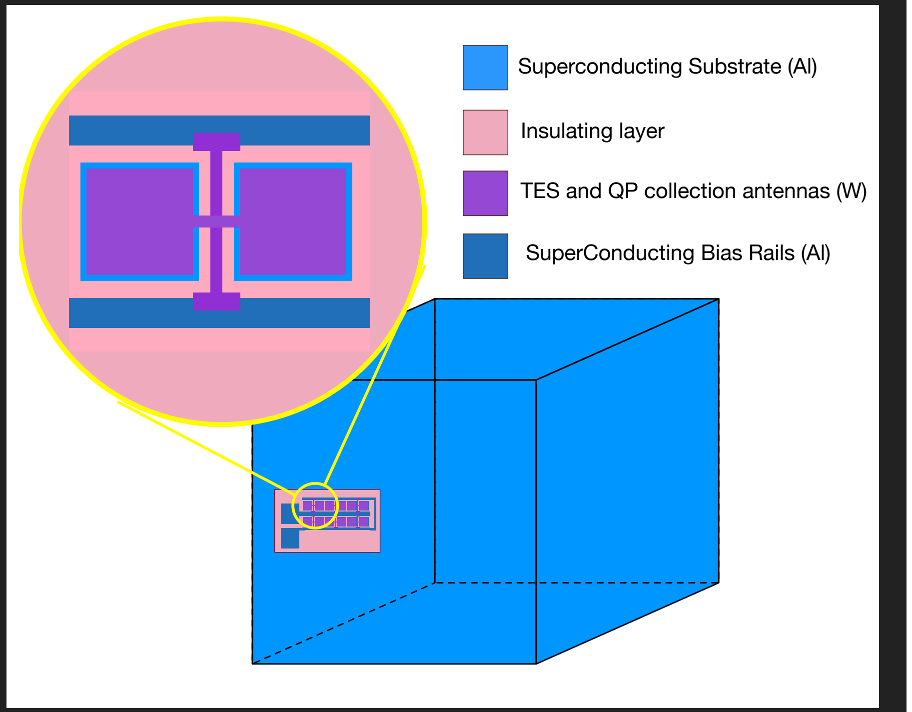
- Large part depends on better energy resolution sensors (TESs); TESs are portable to multiple targets



Semiconductors SuperCDMS

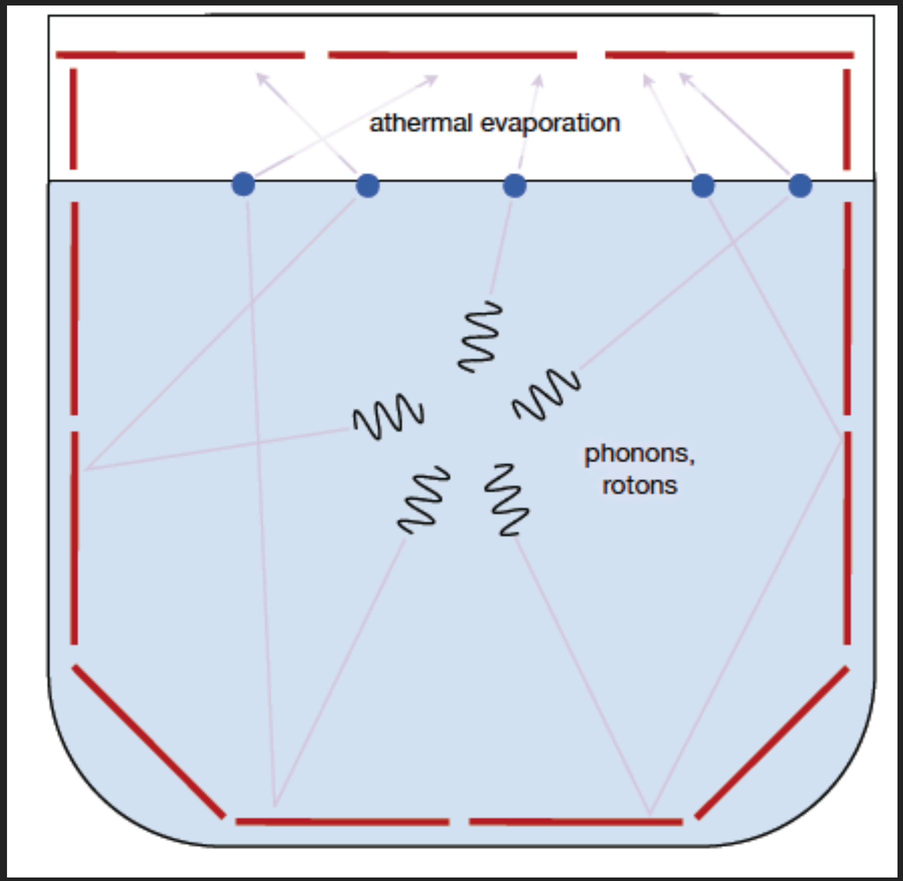
Current energy resolution: ~300 eV

Goal: ~1 eV



Superconductors

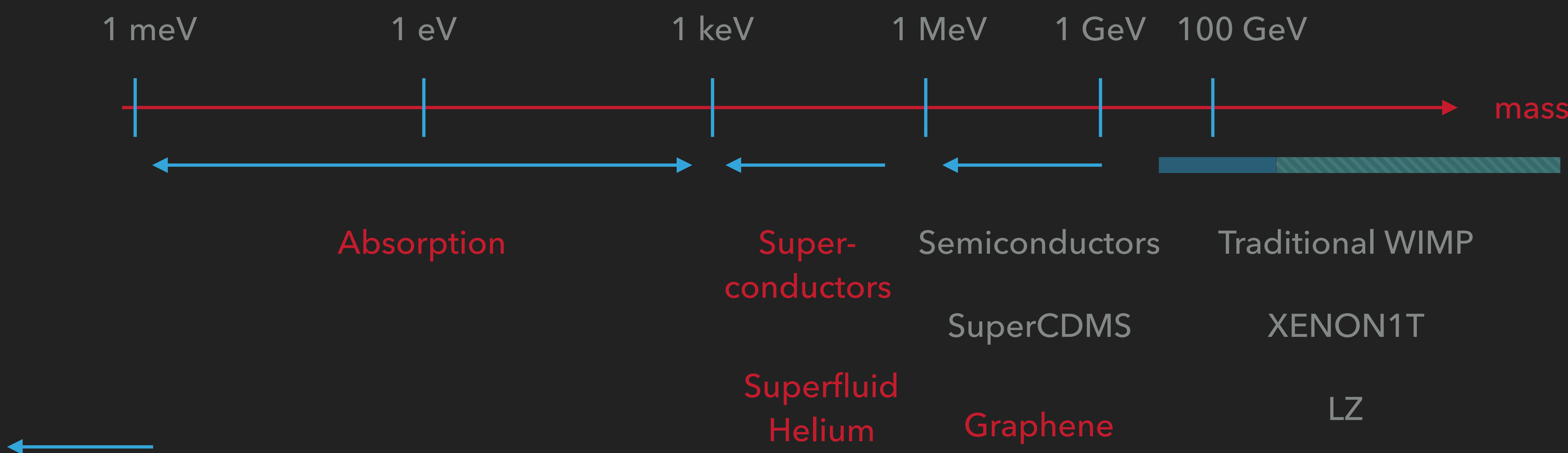
Goal: ~1 meV



Superfluid Helium

Goal: ~1 meV

ROAD FORWARD



Absorption

Super-
conductors

Superfluid
Helium

~meV energy
resolution

Semiconductors

SuperCDMS

Graphene

Scintillators

~eV energy
resolution

Traditional WIMP

XENON1T

LZ

~keV energy
resolution

QCD axion, “ultralight frontier”

See talks tomorrow afternoon,
Friday morning

ROAD FORWARD

- New ideas for dark matter detection!
- Moving beyond nuclear recoils into phases of matter crucial to access broader areas of DM parameter space
- Target diversity essential. What kinds of materials remain to be explored?

ROAD FORWARD

- Leverage progress is materials and condensed matter physics
- Realizing experimental program is 5-10+ years into future
- Every step of R&D for current direct detection experiments (particularly SuperCDMS) can be applied to new dark matter candidates
- Better energy resolution sensors portable between targets
- Nine orders of magnitude increased sensitivity in mass
- Long view necessary!

ROAD FORWARD